Brief article

Neural correlates of the effects of morphological family frequency and family size: an MEG study

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Abstract

Schreuder and Baayen (Schreuder. R., & Baayen, R. H. (1997). How complex simplex words can be. *Journal of Memory and Language 37*, 118–139) report that lexical decision times to nouns are not sensitive to the cumulative frequency of the noun's morphological derivatives in its "morphological family", even though such a cumulative frequency effect is obtained in the domain of inflection. Under a decomposition view of derivational morphology, this constitutes a puzzling exception to the robust finding that lexical frequency is one of the major determinants of behavioral response latencies. If morphologically complex words are decomposed, each occurrence of a member of a noun's morphological family should add to its root-frequency. We investigated the effects of morphological family frequency on the magnetoencephalographic response component M350, which shows sensitivity to factors affecting early stages of lexical processing, including lexical frequency. We hypothesized that high morphological family frequency should have a facilitory effect on the M350, even though no such effect can be seen in response time, presumably due to competition among possible root–affix combinations. Contrary to this hypothesis, we found that high family frequency elicits an M350 inhibition, suggesting that competition among morphological family members occurs at the M350. The result is significant, since there is evidence that competition among phonologically similar words occurs after, not at, the M350. Thus, our results suggest that competition within a morphological family precedes competition within a phonological similarity neighborhood.
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1. Introduction

The effect of lexical frequency is one of the most solid findings in visual word recognition: frequently occurring words are recognized faster than low frequency words across a variety of paradigms and experimental tasks. This effect has also been shown to depend not simply on the superficial frequency of the specific word presented to the subject, but on the cumulative frequency of the inflectional variants of the word (Baayen, Dijkstra, & Schreuder, 1997; Schreuder & Baayen, 1997; Taft, 1979). For example, a singular noun with a high frequency plural form is responded to faster than a singular noun with a low frequency plural form, even if the singular forms themselves are matched for frequency and other relevant factors. Thus, each inflectional instantiation of a particular stem adds to its overall frequency and speeds behavioral response latencies to the stem.

Under a decomposition view of morphological processing (Taft & Forster, 1975), one would expect cumulative frequency effects to occur in the domain of derivation as well. Evidence from the processing of pseudowords containing existing stem and affix morphemes (Taft & Forster, 1975), from masked priming (Rastle, Davis, Marslen-Wilson, & Tyler, 2000) and from the processing of single overtly affixed words (Vannest & Boland, 1999) suggests that word recognition proceeds via the recognition of the morphemic units contained within a word. However, in apparent contradiction with the predictions of decomposition theories, no facilitory effect of high cumulative frequency is obtained for derivation in behavioral responses (Schreuder & Baayen, 1997). The usual result is that cumulative frequency has no reliable effect on reaction times (RTs), but when effects are obtained, they tend towards inhibition for high cumulative frequency, rather than facilitation (Baayen, Tweedie, & Schreuder, 2002; Colé, Segui, & Taft, 1997).

While morphological family frequency does not have straightforward effects on behavioral responses, Schreuder and Baayen (1997) found that the *number* of morphological derivates associated with a root does: lexical decision times to nouns with many morphological derivatives were faster than lexical decision times to nouns with few derivatives. This effect has been taken to be a late decision-stage effect, arising from stronger semantic activation associated with high morphological family size items (de Jong, Schreuder, & Baayen, 2000; Schreuder & Baayen, 1997).

Here we used magnetoencephalography (MEG) in order to determine whether millisecond by millisecond measurements of brain activity might reveal effects of cumulative family frequency in derivation, even though such effects are not obtained in behavior. In particular, we hypothesized that there should be a facilitory effect of high cumulative root frequency at the point of initial lexical activation, which, however, could be rendered unobservable in RT by later competition within a highly frequent morphological family. Competition among morphological family members is suggested, for example, by the fact that facilitation by a suffixed visual target (such as *payment*) is absent when it follows an auditory prime that is morphologically related and also suffixed (such as *payable*) (Marslen-Wilson, Tyler, Waksler, & Older, 1994; but see Pastizzo & Feldman, 2002 on the limits of this effect to cross-modal priming).

To test the hypothesis that cumulative root frequency affects lexical activation, a direct measure of initial lexical activation is needed. In previous work, we have found evidence

that the magnetoencephalographic response component M350 constitutes such a measure. The M350 peaks at approximately 350 ms post-stimulus onset (see Fig. 2) and is generated in the left superior temporal cortex (Helenius, Salmelin, Service, & Connolly, 1999; Pylkkänen, Stringfellow, & Marantz, 2002). The M350 has been found to be the first MEG component in responses to visual words that is sensitive to factors such as lexical frequency (Embick, Hackl, Schaeffer, Kelepir, & Marantz, 2001) and repetition (Pylkkänen, Stringfellow, Flagg, & Marantz, 2001). Crucially, however, the M350 is *not* sensitive to the amount of interlexical competition, which suggests that it is associated with an earlier processing stage than the selection/identification of the best match to the input. The relation between competition and the M350 was investigated by Pylkkänen et al. (2002) who presented participants with stimuli that either came from dense similarity neighborhoods and were associated with a high phonotactic probability or came from sparse similarity neighborhoods and were associated with a low phonotactic probability. In this manipulation, M350 latencies showed the opposite effect of behavioral lexical decision times. High probability/high density stimuli elicited slower lexical decision times than low probability/low density stimuli, due to the higher level of competition within dense similarity neighborhoods. In contrast, the M350 latencies of high probability/high density stimuli were shorter than the M350 latencies of low probability/low density stimuli, presumably reflecting an earlier facilitory effect of high phonotactic probability (i.e. high sublexical frequency). Pylkkänen et al. (2002) concluded that since the M350 is both sensitive to factors such as lexical frequency and insensitive to the amount of competition, it must reflect initial activation of lexical hypotheses, prior to competition. A similar dissociation between the M350 and RT was replicated in a subsequent study where phonological relatedness was manipulated in a cross-modal priming paradigm (Pylkkänen, Stringfellow, & Marantz, 2003). When visual targets such as *reach* were preceded by phonologically similar but morphologically unrelated auditory primes such as *teacher*, M350 latencies were shorter but lexical decision times were longer than when the targets were preceded by unrelated control primes. The M350 facilitation was hypothesized to reflect phonological priming in activation and the RT delay subsequent competition in the selection/identification process.

Given the evidence that the M350 is associated with initial lexical activation, we hypothesized that the M350 might show a decrease in latency and/or amplitude with high family frequency even though no such effect is observable in RT. To assess whether our manipulation was powerful enough to detect a behavioral effect (if present), stimuli contrasting in family size were also presented to subjects. However, if family size indeed affects late stages of lexical processing (Schreuder & Baayen, 1997), the M350 should not show sensitivity to this factor.

The effects of morphological family size and family frequency on lexical decision times have previously been investigated primarily for Dutch. However, the effect of these two factors has been examined in English for another task, namely subjective frequency ratings. For Dutch, Schreuder and Baayen (1997) showed that morphological family size and family frequency affect lexical decisions and subjective frequency ratings in similar ways: both are sensitive to family size but insensitive to family frequency. In a subsequent study Baayen, Lieber, and Schreuder (1997) replicated the subjective frequency result in

English. In the present MEG study, we employed the published materials of Baayen, Lieber, and Schreuder (1997) in a lexical decision task.

2. Method

2.1. Participants

Seventeen right-handed, English-speaking adults with normal or corrected-to-normal vision gave their informed consent to participate in the experiment. Participants were all students or employees at the Massachusetts Institute of Technology and were paid $10 for their participation.

2.2. Stimuli

The stimulus materials in Appendices B and C in Baayen, Lieber, and Schreuder (1997) were used. Morphological families contained both affixed forms as well as compounds. Eighteen nouns with a high family frequency were contrasted to 18 nouns with a low family frequency, while length, frequency of the singular form, the cumulative frequency of the singular and plural forms (stem frequency), neighborhood size and mean bigram frequency were kept constant. Similarly, nouns with a high family size ($n = 21$) were contrasted with nouns with a low family size ($n = 21$), while length, stem frequency and bigram frequency were kept constant. As Baayen et al. mention, in the family size comparison family frequency was not entirely controlled for: nouns with a high family size were also associated with a slightly higher family frequency than nouns with a low family size. The possible effect of this frequency difference will be discussed later in Section 4. Since we wished to use a lexical decision task, these test words were combined with 84 nonwords, of which 40 were phonologically possible words in English and 44 impossible. The mean frequency and family size counts of the four stimulus categories are summarized in Table 1.

While the materials of Baayen, Lieber, and Schreuder (1997) contrasted the stimulus factors that were of interest to us, they were at the margins of practicality for an MEG study, due to the rather low number of stimuli per condition. This increased the amount of

Table 1
Mean frequency and morphological family counts for the four stimulus categories

	Fsg	Fstem	Family size	Family frequency
High family frequency	408.67	491.11	8.33	1256.78
Low family frequency	347.22	459.67	9.39	149.61
High family size	179.76	258.86	15.33	290.00
Low family size	181.86	260.38	1.33	14.29

Fsg, frequency of the singular; Fstem, summed frequency of the singular and the plural.

noise in individual subject data to the extent that no clear M350s were identifiable in the data of seven of the 17 subjects run. However, the ten subjects that did show a clear M350 peak were enough to obtain statistical significance.

2.3. Procedure

During the experiment, participants lay in a dimly lit magnetically shielded room in the KIT/MIT MEG laboratory while visual stimuli were projected onto a ground glass screen in a randomized order. Each trial consisted of a fixation point ($+$) that lasted for 1000 ms followed by the presentation of the stimulus, which disappeared at the button press response. The task was continuous lexical decision. Participants made word decisions with the index finger and nonword decisions with the middle finger of their left hand. The intertrial interval randomly varied between 500 and 1500 ms. Stimuli were presented in nonproportional Courier font, and subtended approximately 1.2° of visual angle vertically and 1.2° per character horizontally. The stimuli varied in length from three to nine letters. As subjects performed the lexical decision task, neuromagnetic fields were recorded using a 93-channel axial gradiometer whole-head system (Kanazawa Institute of Technology, Kanazawa, Japan) at a 500 Hz sampling frequency in a band between DC and 200 Hz.

2.4. Data analysis

For the averaging of the MEG data, an epoch length of 800 ms, plus a 100 ms baseline period, was used. Trials where the subjects responded incorrectly or responded more than 3 SD faster or slower than his/her mean were eliminated both from the MEG averages and the analysis of the behavioral data. This resulted in the rejection of 5.8% of the trials. Artifact rejection excluded all trials that contained signals exceeding ± 2 pT in amplitude and resulted in the exclusion of an additional 5.2% of the trials. The MEG averages for the family frequency comparison contained on average 16 trials (SD $= 1.8$) and the MEG averages for family size comparison 18.3 trials (SD $= 1.9$).

Equivalent current dipole (ECD) analysis was used to estimate the time course of activation in the cortical areas generating the M350 response. The M350 is a primarily left-lateralized component with a posterior outgoing magnetic field and an anterior re-entering field. The M350 localizes to the left superior temporal lobe, very close to the auditory cortex (Helenius et al., 1999; Pylkkänen et al., 2002). Visual inspection of the present data set immediately revealed that M350s were not detectable for many conditions in many subjects, presumably due to the low number of stimuli per condition. Thus, it was crucial to identify those subjects for which the M350 was clearly identifiable and which could therefore be used to test the present hypothesis about the effect of family frequency on the M350. For a subject to be included in the data analysis, we required that the averaged epoch for each of the experimental conditions showed a clear dipolar distribution over the left hemisphere sensors at 300–420 ms post-stimulus onset with the center of the outgoing (or positive) field coinciding with one of the sensors in the red circle in Fig. 1 and the center of the re-entering (or negative) field coinciding with one of the sensors in the blue circle. Ten subjects met these criteria. For these ten subjects, dipoles were localized individually for each subject and condition using
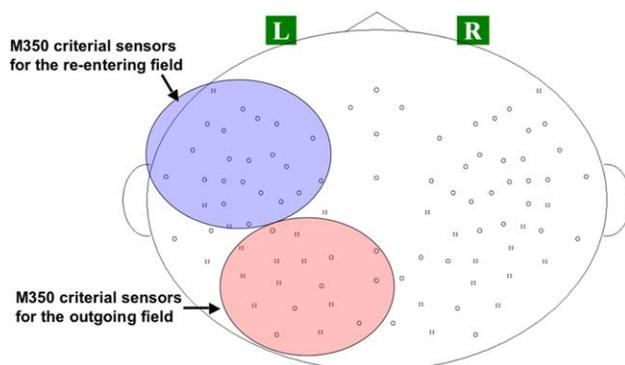
Fig. 1. Criterial sensors for M350 ingoing and outgoing field maxima.

the subset of left hemisphere sensors covering the characteristic M350 field pattern. Dipoles were first fitted for each time point during which the M350 distribution was observed and were allowed to vary in position and orientation in order to obtain the best possible source estimation for each time point. The M350 distribution often persists for over 100 ms and commonly peaks more than once. Our previous results indicate that it is the first peak of the M350 distribution that is sensitive to lexical factors but insensitive to competition, not the onset of the distribution, or the largest peak (Pylkkänen et al., 2002, 2003). Therefore, of the source estimations obtained from the moving dipole analysis, the location and orientation of the dipole corresponding to the first peak of the M350 source were fixed, while allowing its strength to vary over time. From this source wave, M350 latencies and amplitudes were measured individually for each subject and condition at points where the source amplitude reached 25%, 50%, 75% and 100% of the maximum source strength.

In addition to the M350, the latencies and amplitudes of two earlier components were examined: the M170, a bilateral component peaking between approximately 150 and 200 ms, and the M250, a left-lateralized component peaking between 200 and 300 ms (see Pylkkänen & Marantz, 2003 for a review of MEG components elicited by visual words). M250 sources were modeled as ECDs, while the amplitudes and latencies of the M170 were determined from the activity in the sensors corresponding to the extrema of the magnetic field in the left and right hemispheres. Neither of these earlier components have in previous studies shown sensitivity to lexical factors, and were therefore not predicted to be affected by the present stimulus manipulation either.

Finally, to reject implausibly deep source localizations from statistical analysis (as MEG is relatively insensitive to activity in deep sources), we used a rather crude criterion across subjects and required that the sum of the absolute values of the x, y and z coordinates of each dipole be more than 10 cm. This resulted in the rejection of nine dipoles out of a total of 72 localizations at M250 or M350 peaks. The mean goodness of fit of the accepted dipoles was 90%.

3. Results

In the behavioral data, the same pattern of RT results that Schreuder and Baayen reported for Dutch were obtained here for English: lexical decision times to nouns with a high family size ($\bar{x} = 688$ ms) were faster than responses to nouns with a low family size ($\bar{x} = 731$ ms, $F(1,9) = 6.68$, $P < 0.05$) while morphological family frequency had no reliable effect on response latencies ($F(1,9) = 1.86$), although numerically nouns with a high family frequency were responded to more slowly ($\bar{x} = 749$ ms, SD $= 253$) than low family frequency stimuli ($\bar{x} = 705$ ms, SD $= 176$), which is consistent with the findings of Colé et al. (1997). Error rates showed no reliable sensitivity to the stimulus manipulations.

While the behavioral results conformed to expectations, the MEG data patterned in surprising ways. Fig. 2 depicts the overlaid time course of the averaged MEG data and the M350 dipole localizations for all four experimental conditions for one representative subject. No indication of a latency or amplitude reduction is observable for the M350 elicited by nouns with a high family frequency. Instead, high family *size* seems to be associated with an M350 latency reduction. Analyses of variance (ANOVA) on M350 source latencies and amplitudes verified this pattern of results to be reliable across subjects (Fig. 3). There was no reliable effect of family frequency on M350 latencies either at the peak of the source ($F(1,8) = 2.8$, $P = 0.15$) or at any of the measured points on
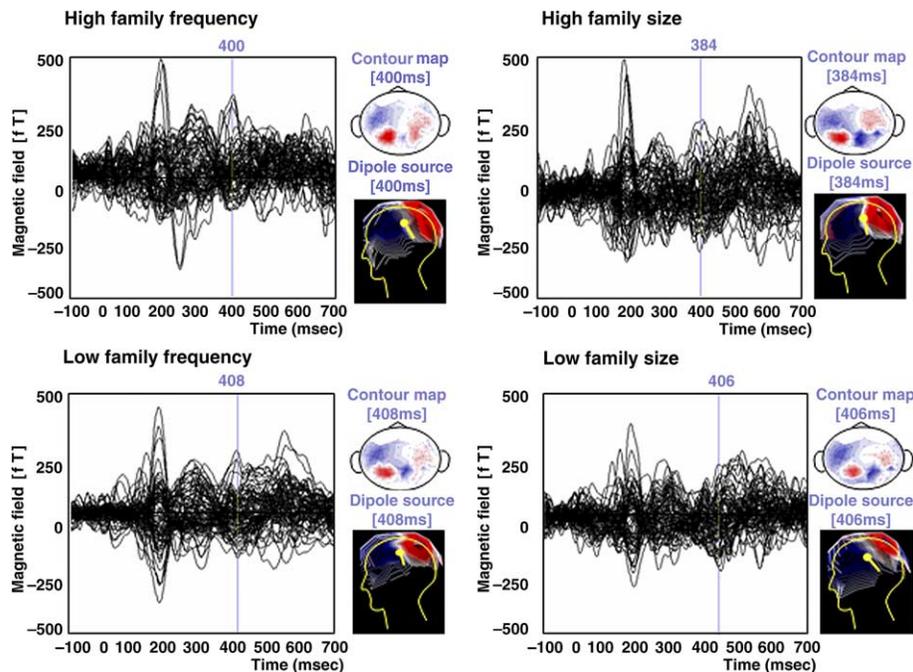

Fig. 2. The overlaid time course of the averaged MEG data and the M350 dipole localizations for all four experimental conditions for one representative subject. The cursor points at the M350 peak latencies.
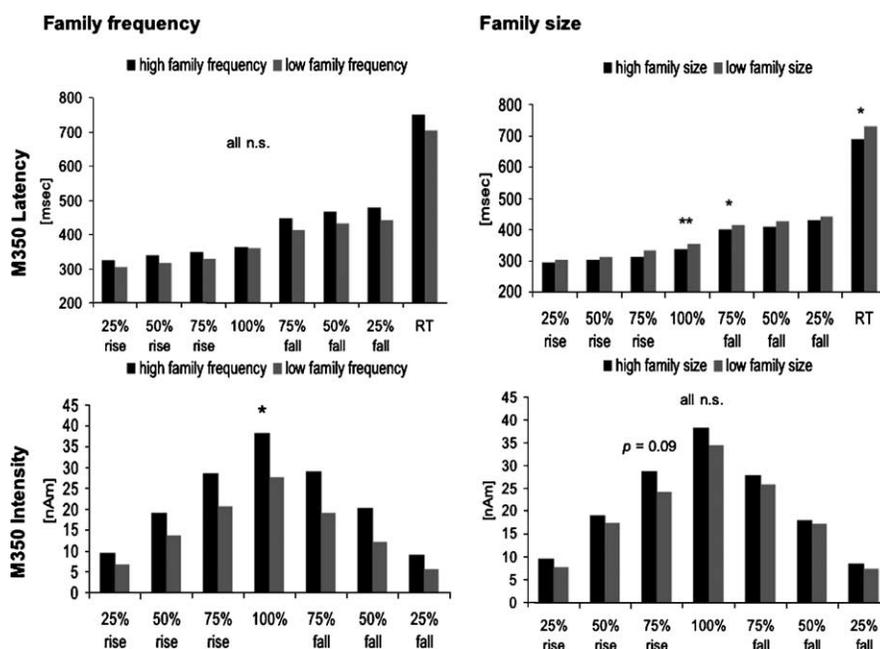
Fig. 3. Effect of family frequency and family size on RTs and the M350.

the ascending or descending slopes of the source wave (all $F < 1$). A general trend towards longer latencies for high family frequency items was, however, observed, suggesting inhibition. In contrast to the latency data, in the amplitude data a clear inhibitory effect of high cumulative frequency was obtained. The M350 sources of high family frequency items were associated with larger amplitudes ($\bar{x} = 39.23$ nAm) than the M350 sources of low family frequency items ($\bar{x} = 27.66$ nAm, $F(1, 8) = 7.6$, $P < 0.05$), indicating an inhibitory effect of high family frequency at the M350. This inhibitory effect was observed at all points on the ascending and descending slopes of the source, although it was reliable only at the M350 peak.

The M350 latency reduction by high family size apparent in the individual subject data was reliable across subjects, the M350 sources of high family size items peaking earlier ($\bar{x} = 336$ ms) than the M350 sources of low family size items ($\bar{x} = 354$ ms, $F(1, 9) = 14.5$, $P < 0.01$). This reduction in latency reached significance not only at the M350 peak, but also at the point where the M350 source exhibited 75% of its maximum source intensity at the descending slope ($F(1, 9) = 6.9$, $P < 0.05$). Family size had no reliable effect on M350 amplitudes (all $F < 1$ except at the point where the source intensity reached 75% of its maximum intensity in the ascending slope, $F = 4.1$, $P = 0.09$).

Finally, the stimulus manipulation had no reliable effects on the amplitudes or latencies of the earlier M250 or M170 components. Consistent with previous results (Pylkkänen et al., 2002), the M250 localized more left-laterally ($F(1, 9) = 6.5$, $P < 0.05$) and more posteriorly ($F(1, 9) = 19.38$, $P = 0.0001$) than the M350 source. Further, even though

the M250 and M350 components are in many cases associated with similar magnetic field patterns (Pylkkänen et al., 2002), their source orientations were found to differ reliably both in altitude ($F(1, 9) = 26.3$, $P = 0.0001$) and in rotation ($F(1, 9) = 8.2$, $P < 0.01$). This verifies that the M250 is indeed generated by a distinct cortical region from the M350.

4. Discussion

The aim of the present study was to determine whether properties of the M350 MEG component would provide evidence of facilitation by high cumulative root frequency in the domain of derivation, even though no such effect is obtained in behavioral responses. A decomposition view of derivational morphology clearly predicts that at least at some point in the course of lexical processing high root frequency should have a facilitory effect. We hypothesized that this effect should be observable at the point of lexical activation, which prior results suggest is indexed by the M350. In order to explain the null behavioral effect, we reasoned that early facilitation by high family frequency could plausibly be cancelled out by subsequent competition between possible root–affix combinations. This type of dissociation between the M350 and RT had previously been obtained by Pylkkänen et al. (2002, 2003) when phonological stimulus factors were manipulated.

Our results, however, indicate that instead of eliciting an M350 speed-up, high family frequency is associated with an extra processing load at the M350, evidenced by increased M350 amplitudes for high family frequency stimuli. This suggests that morphological competition, which we hypothesize to be responsible for the lack of a behavioral facilitation by high cumulative frequency, occurs already at the M350. Crucially, there appears to be a time course difference between phonologically based and morphologically based competition, the former occurring after the M350 (Pylkkänen et al., 2002), and the latter at the M350. Since morphological relatives seem to compete with each other earlier than phonological neighbors, an explanation of the present results requires that morphological relatives stand in a qualitatively different relationship to each other than phonological neighbors. Thus, the present results yield support for decomposition theories, although the evidence is not of the sort originally envisioned.

The finding that morphological effects occur early in processing conforms well to recent results from masked priming where primes that only appeared to be morphologically related to their targets (corner-CORN) elicited an equivalent priming effect to primes that actually were morphologically related to their targets (cleaner-CLEAN) (Rastle & Davis, in press; Rastle, Davis, & New, 2003). In contrast, primes that were only formally related to their targets (brothel-BROTH) elicited no significant priming. The authors of the study suggest that there is an early process of morphological parsing and segmentation that is based purely on the formal properties of the stimulus. This proposal is also consistent with evidence from electrophysiology, suggesting that word category, which depends on the morphological properties of the stimulus, is determined early, prior to lexical processing (Friederici, 2002).

If morphological parsing occurs early, one would expect morphological competition to occur early as well, which is what our results suggest. A question that remains is precisely

how early this competition effect begins. This is underdetermined by the present study, where M350 inhibition was reliable at the M350 peak, but source amplitudes tended towards inhibition already at early points of the ascending slope of the source wave, suggesting that competition might be occurring even before the M350.

Contrary to our expectations, family size also modulated the M350, high family size speeding up M350 latencies. This straightforwardly reflects the facilitory effect of high family size on behavior. That a factor such as morphological family size should affect the M350 is quite surprising; this does not follow from any of our current assumptions about the functional significance of the M350, nor is it consistent with Schreuder and Baayen's (1997) proposal that family size affects processing postlexically, at the decision stage. Could the observed effect of family size on the M350 be due to family frequency instead, as this factor was not entirely controlled for in the family size comparison? We consider this unlikely since family frequency had no effect on M350 latencies in the family frequency comparison where this factor was explicitly manipulated. Thus, further experimentation is clearly needed in order to elucidate the nature of the morphological family size effect.

Acknowledgements

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